INFRARED DETECTOR REQUIREMENTS WHICH DRIVE CRYOGENIC DEVELOPMENT

Robert E. McMurray, Jr.

NASA Ames Research Center
M/S 244-10
Moffett Field, CA 94035-1000

In recent years infrared detector technology has progressed from simple discrete detectors, which still represent the state-of-the-art at some infrared wavelengths, to large multiplexed 2-dimensional arrays of detector pixels. This evolution has increased the heat load at the focal plane for the detector coolers. Also, there is an increasing move toward more electronics on the focal plane itself, and the cryogenic burden can be substantial. In this paper I will discuss a number of different detector technologies aimed at various wavelength regimes. Each of the devices has its own optimum operating temperature, and the heat load at that temperature is determined both by the readout electronics and the infrared loading on the focal plane. In general, for lower noise readout operation using conventional FET first stage readouts, increasing the current (and therefore power) on the FET decreases the noise in the channel. For the lowest background observations this power is dominant. At higher infrared backgrounds FET noise is less important, but the optical power on the focal plane can become significant. I will survey and compare power and temperature requirements for a broad spectrum of detector types.

Keywords: infrared detectors, bolometers, photoconductors, BLIP, noise

INTRODUCTION

Detection of infrared radiation is an important application of state-of-the-art technology in a mix of several fields of study. It brings together the specialty areas of solid state physics, low-noise electronics, cryogenics, and statistical analysis, as well as the application areas of astronomy, 2-dimensional imaging, and spectroscopy. For particular applications in low-background astronomy or high-resolution spectroscopy, the infrared detector/amplifier combination used must be capable of operating at the photon-noise limit of performance. This is especially true for cooled telescopes operating in space, such as NASA's planned Space Infrared Telescope Facility (SIRTF)[1]. The infrared photon background fluxes in such cases are very near zero, and extremely small signal fluxes must be distinguished from any other background noise sources such as electronics or detector noise.

Previous versions of space-based telescopes, such as NASA's Infrared Astronomical Satellite (IRAS)[2], made use of discrete detectors for single-pixel images of the infrared sky. Detector technology has progressed in recent years to the development of large-area 2-dimensional detector arrays capable of operating near photon noise limits over a large portion of the infrared spectral range. These new detectors require additional cryogenic considerations in terms of the electrical heat dissipation of the detector package on the focal plane, as well as the larger areas of focal plane subjected to photon heat loading from the sky.

This paper attempts to give some insight into the thermal requirements for specific classes of infrared detectors. Operating temperatures depend on the type of detector material (such as a particular intrinsic or extrinsically-doped semiconductor), the configuration of the detector (i.e., photovoltaic or photoconductive) and the desired photon flux and corresponding noise limit. Heat loads depend both on the infrared background and on the focal plane electronics. Heat conduction along wire leads from the focal plane to the warm electronics can also be an issue but will not be discussed in this limited review.

NOISE SOURCES

There are four main sources of noise that concern us for this discussion of detector requirements. They are: (i) Johnson or white noise, (ii) flicker or 1/f noise, (iii) generation-recombination noise, and (iv) shot noise. These independent noise sources, added in quadrature, determine at each frequency the photon flux required for photon noise to dominate system noise, and thus achieve background-limited performance (BLIP). The combination of detector and associated electronics noise will then determine the type of detector required for a particular application, and therefore the operating temperature as discussed in the next section.

The Johnson (Nyquist) noise source originates in thermal fluctuations affecting the charge carrier movement in any conductor. Both detectors and the electronics which they require, such as load or feedback resistors and FET input amplifiers, are subject to Johnson noise according to the definition:

$$N_J = (4kTR)^{1/2} \qquad \text{volts}/(\text{Hz})^{1/2}$$

where R is the electrical resistance of the device at the temperature T. This noise can be dominant in the higher-frequency operating regimes.

Flicker noise, typically a noise mechanism that creates a frequency (f) dependent noise voltage inverse in some power of the frequency, can be caused by trapping states in the detector bulk or surface, and by carrier trapping along the channel of the FET amplifier. This noise dominates at lower operating frequencies. The noise voltage is proportional to a prefactor $V_n(T)$ times an inverse power of f; V_n can in some cases have an Arrhenius dependence on the specific trap energy with temperature $V_n \sim \exp(E/kT)$, and is given by:

$$N_f = V_n(T)/f^n \qquad \text{volts}/(\text{Hz})^{1/2}.$$

Generation-recombination noise is due to the random nature of the process of creation of a free charge carrier in a detector, and of the subsequent recombination or trapping loss of the carrier. It can be computed as:

$$N_{gr} = 2\,I\,(\tau/N(1+(2\pi f\tau)^2))^{1/2} \qquad \text{ampere}/(\text{Hz})^{1/2}.$$

where I is the current through the detector, N is the total number of free carriers, and τ is a characteristic lifetime. This noise can be dominant in an intermediate frequency regime between the above two mechanisms.

Shot noise is due to the discrete nature of the electronic charge carriers (electrons and holes, charge quantum e) which form a current I. It is given by:

$$N_s = (2eI)^{1/2} \quad \text{ampere}/(\text{Hz})^{1/2}.$$

This noise is typically lower than the Johnson noise of the system, but can be an important fractional current noise at very low currents. This is the reason that input FETs must be run at a minimum channel current in order to achieve a low system noise limit. In cases of large arrays of detectors, the power dissipated to pass this amount of current through the FET channels is a large source of heat at the focal plane.

It must be remembered that the ultimate noise goal desired is the limit of the noise inherent in the photon stream incident on the detector. Photons from a blackbody are subject to Bose-Einstein fluctuation statistics, but for the purposes of measurement of a small flux from a source such as in IR astronomy the statistics are approximately equal to Poisson statistics in which the noise in the number of photons arriving in a given time is simply the square root of that number of photons. For a given photon flux, the photon noise limit is reached when the combination of detector and electronics noise is less than the fluctuations in the photon stream. This therefore determines the type of detector and electronics needed for a particular measurement application, and thus the temperature and power dissipation required.

DETECTORS

The type of detector used for any given application depends on the wavelength of operation required, as well as the sensitivity requirement and the photon flux. In turn, the choice of detector will determine the requirements for temperature of operation, thermal stability and cooling power. The aspect of thermal stability, as it relates to radiometric stability of the detector has been treated previously[3] and will not be reviewed here. The present discussion will focus on the required temperature of operation for a range of detector types, with some mention of the power dissipation in particular cases. The aim is to present a discussion of the reasons for operation of particular detectors at specified temperatures.

In the infrared, detectors can be classified into two broad basic categories: thermal detectors and photon (or quantum) detectors. As the names imply, the thermal category consists of those devices which respond to a change in device temperature alone, while the photon category consists of devices which respond directly to individual photons and whose signal output is linear in the number of photons absorbed.

Detector figures of merit typically specified are responsivity (R), noise equivalent power (NEP), and detectivity (D*). It is important to realize that the absolute responsivity of any individual detector is not relevant for comparison purposes, so long as the noise associated with that detector allows the achievement of a given noise equivalent power or detectivity. The only real criterion for responsivity is that it be large enough to lift the smallest required signal out of the system noise, typically limited by the input electronics stage or FET. Thus the noise of the system, relative to the photon noise for the lowest required signal, determines the limits of detector performance.

A. THERMAL DETECTORS

There are a number of types of thermal detectors in use today. These consist of: (i) bolometers, such as semiconductor (Ge or Si) or superconducting transition-edge materials, (ii) thermovoltaic devices, such as the thermocouple and thermopile, (iii) thermopneumatic devices which rely on gas expansion, as in the Golay cell, and (iv) pyroelectric devices, notably DTGS and $LiTaO_3$ at room temperature. The one common aspect of all of these types of thermal detectors is that they are all limited by the thermal fluctuation noise from the temperature bath. That is to say, no matter what the thermal detection mechanism, it is impossible for any thermal detector to have lower noise than the so-called '"thermal limit", given by[4] the power fluctuations δW_T through the thermal link:

$$\delta W_T = (4kT^2G)^{1/2}.$$

The weakest possible thermal link G is given by the radiatively coupled limit, in which the noise power for a device of area A is just:

$$P_N = (16A\sigma kT^5)^{1/2}.$$

For infrared detection applications which involve large photon fluxes, in which the photon noise limit is high, such detectors can achieve the condition of thermal limit < photon limit at moderate temperatures (100K-200K). However, in low-background astronomical applications the photon noise limits are so small that the detector bath temperature must be reduced to levels of the order 100mK to decrease the thermal fluctuation noise to the point where these limits can be approached.

In general, detectors such as the pyroelectric, Golay cell, and thermopile are only useful in very high-background applications. Space-based platforms such as NASA's Earth Observing System (EOS) may contain detectors of near- and mid- infrared radiation which are subject to a nearly 2π-sr view of the Earth as a 300K blackbody. These high-background applications of detectors can reach photon noise limits with only the moderate cooling requirements of 100K-200K, depending on the spectral limits of the flux they are subjected to. Heat loading in these cases is dominated by the thermal flux of infrared radiation on the detector and absorber.

Bolometers, on the other hand, and particularly the elemental semiconductor bolometers, are capable of operation at temperature well below that of liquid helium. This brings up the possibility that these devices can detect infrared radiation at the photon noise limit if the temperature can be made cold enough. Since quantum detectors of infrared radiation, even at far infrared wavelengths, do not require this level of cooling it is usually the case that bolometric detectors are advantageous only at wavelengths in the submillimeter range at which no good quantum detectors exist. For this reason, detection of wavelengths beyond 200μm is usually done by discrete semiconductor bolometers operating at temperatures below 300mK. The cooling power requirements are typically dominated by absorbed photon heat load and thermal conductance of leads and supports to the higher temperature stages. In many cases the first amplification or impedance-transformation stage, typically a FET, is not maintained at the bolometer temperature. In these cases, the electrical heat load at the focal plane is not dominant.

B. PHOTON DETECTORS

Many types of individual photon detectors exist, at a wide range of wavelength cutoffs (λ_c). Most of the important detectors of interest consist of either intrinsic semiconductors (λ_c determined by the band gap) or extrinsically-doped semiconductors (λ_c determined by the dopant ionization energy). Direct detection by superconducting tunnel junctions, as well as heterodyne detection techniques, are also in use. However, these latter detectors tend to be important only at the very longest infrared wavelengths and will not be discussed further here. The thermal requirements for photon (quantum) detectors are determined mostly by the quantum ionization energy E_i, related to λ_c by

$$E_i\lambda_c = hc = 1240\text{eV-nm} = 1240\text{meV-}\mu\text{m}.$$

The two main categories of semiconductor quantum detectors are photovoltaic (PV) and photoconductive (PC). These two differ in the mechanism of charge collection, as determined by the electrical contacts. In a PV detector, the semiconductor is contacted as a diode, i.e., a p-n junction device. This may be accomplished either by ohmic contacts of two different carrier types, one p contact and one n contact, or by Schottky-barrier contacts (this paper will not discuss the internal-photoemission Schottky barrier detectors such as PtSi). The absorbed photon generates an electron-hole pair, and the carriers are separated to opposite polarity contacts by the internal field of the junction plus any external applied electric field. This type of detector has the advantage of lack of recombination noise, which reduces internal detector noise by the square root of two over G-R limited photoconductors. Also, it is typical that the thermal generation of carriers band-to-band in an intrinsic PV device is smaller than that in an equivalent $□_c$ extrinsic PC detector.

In a PC detector, both electrical contacts are of the same impurity type, either both p or both n depending on the bulk type of the semiconductor used. In this type of detection mechanism, a single carrier of a given sign is liberated by absorption of a photon at an energy above the ionization energy of the principle dopant (Multi-Quantum Well Detectors and Strained Layer Superlattices are similar, but carriers are emitted from a bound state in the well). The free carrier is swept out toward the contact as a photocurrent by an externally applied electric bias field. After drifting a mean path length in the detector, the carrier is randomly lost to recombination at an ionized dopant site. The average number of free carriers at a given time is determined by the photon absorption generation rate (g) and the free carrier lifetime (□) which is given by the recombination coefficient (B) and the density of ionized sites for recombination. In an n-type PC (concentration of donors N_d > concentration of acceptors N_a), the steady state photon generated carrier concentration n is given by:

$$n = g□ = g/B(N_a+n).$$

In low-background astronomical detection this is a very small number of electronic charges and must be made larger than any thermally-generated carriers in order to achieve the photon noise limit. The thermal generation in any particular semiconductor can be calculated by detailed balance using semiconductor statistics and band parameters to obtain[5], for n-type detectors,

$$n = (2/□)\,((N_d-N_a)/N_a)\,(2\pi m^*kT/h^2)^{3/2}\exp(-E_i/kT)$$

at thermal equilibrium, where E_i is the ionization energy. In the first factor, □ is the dopant spin degeneracy, usually 2 or 4, so this factor is of order 1. The next factor is the inverse of the compensation in the semiconductor (K), where values of K typically range from 10^{-2} to 10^{-4}. This factor leads to an increase in the number of states ionized compared to the PV case in which this factor is absent. This requires the PC detector to be held at a lower operating temperature than an equivalent ionization energy PV detector in order to reduce the thermal exponential term to make up for ionized compensation sites. The final two terms give the steady-state thermal ionization in the equivalent PV detector and are just the equivalent band density of states (N_c, depending on the effective mass m*) and the Boltzmann factor. In the PV case, m* is the geometric average of both conduction and valence bands. Figure 1 shows the dependence between the temperature required for a given energy gap E_g of intrinsic PV detector in order for the thermal generation to be less than the photon generation, at a number of different photon fluxes. This assumes an absorption depth of 10μm and a lifetime of 1sec.

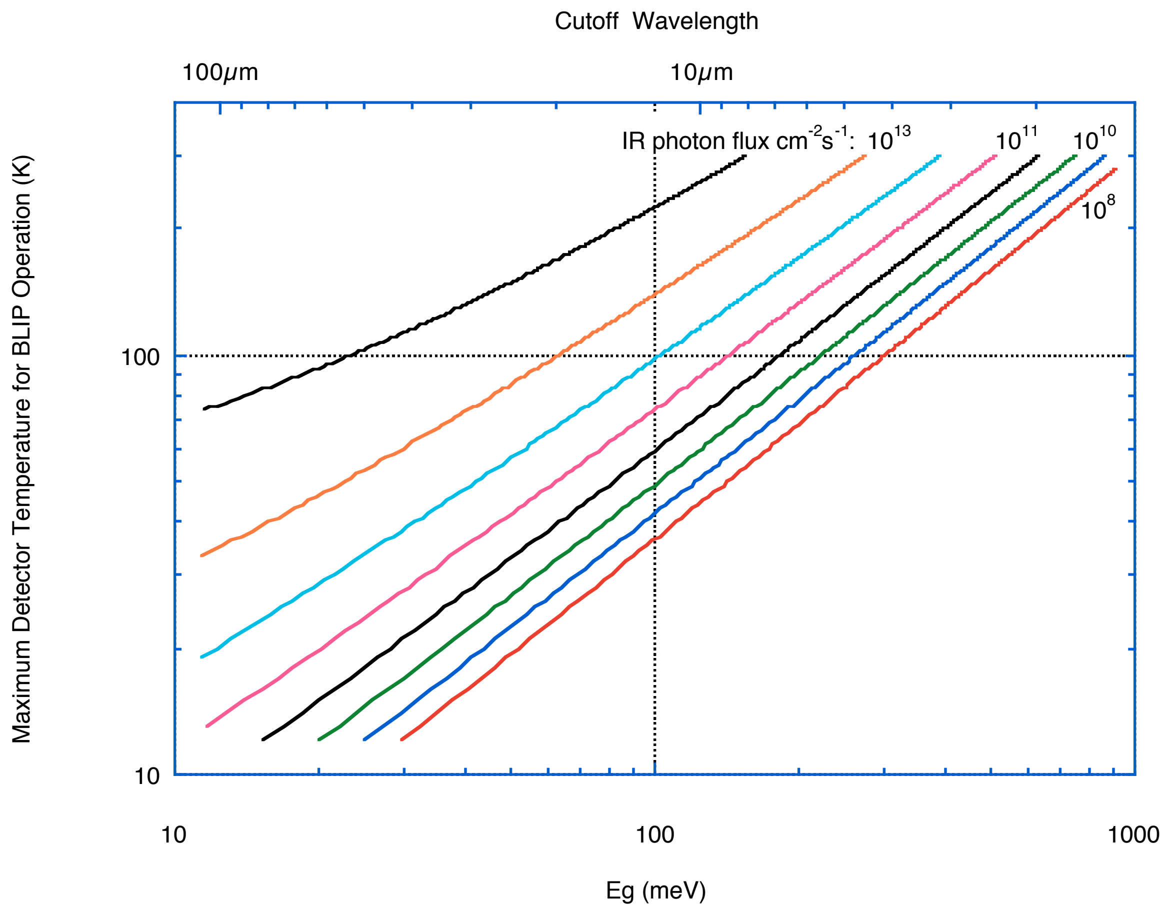

Figure 1. Temperature requirement for BLIP intrinsic detector vs. E_g.

One additional type of quantum detector is worth special mention at this point, because it is a cross between PC and PV detection. The Blocked Impurity Band (BIB) detector consists of a highly extrinsically-doped infrared active layer which is subject to hopping conduction of ionization states of the dopant. This conduction would cause leakage and dark current, so an undoped layer is grown on top of the active layer to block the hopping mechanism. This detector makes use of a single polarity electrical contact, as in PC detectors, since it operates using carriers freed from dopant atoms by photoionization. However, because the residual ionized dopant site is mobile, it acts as an opposite-sign carrier as in a PV detector, but with very low carrier mobility. The detector is polar in the sense that the bias must be applied in a particular direction for proper operation.

The advantage in terms of noise is the elimination of the recombination mechanism under nominal bias conditions. However, due to thermal ionization of the shallow dopants, the operating temperatures required are similar to those of an equivalent cutoff PC detector.

C. SEMICONDUCTOR DETECTOR TYPES

The four types of semiconductor material most commonly used as detectors are as follows: (i) Elemental (Ge:Au, Hg, Cd, Cu, Zn, Be, Ga, B, Al; Si:In, Ga, As, Sb), (ii) III-V (InGaAsSb) alloy range 0.84μm-6μm, (iii) II-VI (HgCdTe), and (iv) IV-VI (Lead salts). The listing gives many of the extrinsic dopants for the elemental semiconductors Si and Ge. The possible wavelength range attainable for different II-VI compounds of the elements given is listed, and the ranges for the II-VI and IV-VI compounds are limited at the long-wavelength end by electrical contact technology, since zero bandgap can be achieved. The following table summarizes the ionization energies, wavelengths, and operating temperatures:

Detector	Energy (meV)	λc (μm)	Typical Temperature (K)
Ge (PV)	670	1.85	77-100
Ge:Au	150	8.25	20-77
Ge:Hg	91	13.6	25-60
Ge:Cd	55	22.5	6-10
Ge:Cu	43	29	4.2-10
Ge:Zn	30	41	4.2-8
Ge:Be	24	52	4.2-8
Ge:Ga	11	113	2-4.2
Ge:B	10.6	118	2-4.2
Ge:Al	10	124	2-4.2
Stressed Ge:Ga	6.2	200	1-3
Si (PV) CCD	1100	1.125	215-300
Si:In	160	7.75	30-77
Si:Ga	72	17	6-10
Si:As	54	23	4.2-10
Si:Sb	43	29	4.2-8
GaAs	1500	0.84	300
InAs	350	3.5	77
InSb	200	6.25	12-77
Pb_8Sn_2Te (PC)	100	12.4	4.2-77
PbS	440	2.8	77-300
Hg_8Cd_2Te (PV)	88	14	65-90

The main considerations that determine the actual temperature of operation are the required photon flux and the leakage current. At the lowest background fluxes the noise in the leakage current can dominate unless the temperature is low enough to reduce the thermally generated leakage below this level. The ranges given in the table cover most of the operation of the detectors, from lowest leakage values to quite high temperatures suitable only for high-background flux detection.

HEAT LOADS

There are several mechanisms for heat dissipation on the focal plane. The primary one of concern for a large-area focal plane array is electrical power dissipation. In the typical array multiplexer, the pixels have a source-follower FET for each detector, and each of these FETs must have a minimum channel current in order to read out the detector signal. Aside from the consideration of R-C time constants which require higher power FET dissipation to reduce impedance's, the relative current noise in the FET channel is reduced as the current is increased. Typical power dissipation directly on the focal plane is of the order of 1mW or less for slow readouts, but can easily pass tens of mW at high readout rates.

Additional heating sources are the thermal leaks due to the large number of connection wires required for a typical large-format 2-dimensional array and the optical power absorbed on the focal plane itself. Optical filtering to limit bandwidth may help to reduce the infrared heat load, but it is generally necessary that the filters be cooled in order to reduce emissions. Thus, both the emissivity of the blackbody observed, such as a large solid angle of the Earth at 300K, and the solar reflectance from the observed body contribute to heating. For a meter-class telescope, the reflected light can represent loading of several mW per square cm by itself.

In some intermediate temperature applications, much more of the detector electronics than just the first stage FET amplifier are placed at the focal plane. It is possible to incorporate a complete transimpedance amplifier per detector by using z-plane technology with 2-dimensional focal plane arrays. In applications requiring the fastest read rates, typically high-background detectors operating above 77K, all analog electronics including the A/D converters can be included. The power dissipated in all of these electronic elements appears as a heat load directly on the focal plane. These loads can approach several watts of power.

CONCLUSIONS

The operating temperature and focal plane cooling power for a given detector is determined by a combination of parameters. Foremost of these is the required cutoff wavelength for the observation, which fixes the bandgap and type of detector. Next, the minimum photon flux to be measured is used to determine the maximum leakage current, and therefore temperature, of the chosen detector. The photon noise in the minimum flux also determines the maximum electronics noise that can be tolerated in order to remain background-limited. The electronic noise requirement implies a minimum current flow through the front-end FET stage, typically a source follower, to reduce the relative current noise. This in turn usually is the dominant heat dissipation on the focal plane, for low light backgrounds, and therefore sets the cooling power requirements.

---

[1]Werner, M.W., "Scientific Goals of the SIRTF Mission" in Infrared and Millimeter Wave Engineering, Hal Busher, Ed., Proc. SPIE Vol. 1874-28 (1993).

[2]Rosing, D., IRAS End of Mission Report, Jet Propulsion Laboratory document number JPL D-1547.

[3]Vorreiter, J.W. and McCreight, C.R., "Cryogenic Cooling Requirements of Photoconductive Infrared Detectors for Orbiting Astronomical Telescopes", Proceedings of the Conference "Applications of Closed-Cycle Cryocoolers to Small Superconducting Devices", J.E. Zimmerman and T.M. Flynn, Eds., Oct. 3-4, 1977, pp. 153-7 (1978).

[4]Putley, E.H., "The Pyroelectric Detector" in Semiconductors and Semimetals Vol. 5, Willardson and Beer, Eds., pp.259-285 (1970).

[5]Bratt, P.R., "Impurity Germanium and Silicon Infrared Detectors" in Semiconductors and Semimetals Vol. 12, Willardson and Beer, Eds., pp.39-142 (1977).